7. Waves

including UFOs, earthquakes, and music

19 October 2004

Two strange but true stories

The following two anecdotes are actually closely related, as you will see later in this chapter. They both will lead us into the physics of waves.

1. "Flying Saucers" crash near Roswell New Mexico

In 1947, devices that the U.S. government called "flying disks" crashed in the desert of New Mexico. The debris was collected by a team from the nearby Roswell Army Air Base, which was one of the most highly classified locations in the United States. The government put out a press release announcing that flying disks had crashed, and the story made headlines in the respected local newspaper, the Roswell Daily Record. Take a moment to look at the headlines for July 8, 1947: RAAF Captures Flying Saucer. (RAAF stands for Roswell Army Air Force.)

The next day, the U.S. Government retracted the press release, and said it was in error. There were no flying disks, the government said. "It was only a weather balloon." Anybody who had seen the debris knew it wasn't a weather balloon. It wasn't. The government was lying, in order to protect a highly classified program. And everybody knew the government was lying.

The story I have just related sounds like a fantasy story from a supermarket tabloid -- or maybe like the ravings of an anti-government nut. But I assure you, everything I said is true. The story of the events of Roswell New Mexico are fascinating, and not widely known, since many of them were classified until recently. In this chapter I'll fill in the details that will make the Roswell story make sense.

Incidentally, if you are unfamiliar with the name Roswell, that means you have not watched the TV program "The X-Files" or read any of the other voluminous literature about flying saucers and UFOs. Try doing a web search on Roswell 1947 and see what you find. Be prepared to be astonished.

2. Rescuing pilots in World War II

The true story of the flying disks began with an ingenious invention made by the physicist Maurice Ewing near the end of World War II. The invention involved small objects called "sofar" spheres that were in the emergency kits of pilots flying over the

Pacific Ocean. If the pilots were shot down, but they managed to inflate and get on to a life raft, then they were instructed to take one of these spheres and drop it into the water. If they weren't rescued within 24 hours, then they should drop another.

What was in these miraculous spheres? If the enemy had captured one, and opened it up, they would have found that the spheres were hollow, with nothing inside. How could hollow spheres lead to rescue? How did they work?

Here's the answer: Ewing had been studying the ocean, and he was particularly interested in the way that sound travels in water. He knew that the temperature of the water got colder as it got deeper -- and that should make sound travel slower. But as you go deeper, the pressure gets stronger, and that should make the sound travel faster. The two effects don't cancel. When he studied it in detail, he concluded that the sound velocity would vary with depth. And his most interesting conclusion was that at a depth of about 1 km, the sound traveled slower than at any other depth. As we will discuss later, this implies the existence of a "sound channel" at this depth, a layer that tends to concentrate and focus sound and keep it from escaping to other depths. Ewing did some experiments off the coast of New Jersey, and verified that this sound channel existed, just as he had predicted.

The sofar spheres were hollow, heavier than an equal volume of water (so they sank), and strong enough to hold off water pressure until they reached the depth of the sound channel. At that depth the sphere suddenly collapsed, and sent out a pulse of sound that could be heard thousands of kilometers away. From these sounds, the Navy could figure out the approximate location of the downed pilot, and send out a rescue team.

It turns out (this wasn't known back then) that Ewing's little spheres used the same phenomena that whales use to communicate with other whales: the focusing of sound in the sound channel. We'll discuss this shortly.

At the end of World War II, the same Maurice Ewing proposed a second project, based on the same idea, that was eventually given the name "Project Mogul." It used "flying disks" for a highly classified purpose: to detect nuclear explosions. It made use of a sound channel in the atmosphere. But the flying disks crashed in Roswell New Mexico in 1947, made headlines, and became part of a modern legend.

To explain these stories, we have to get into the physics of sound. And to understand sound, we have to talk about waves.

Waves

All waves are named after water waves. Think for a moment about how strange water waves are. Wind pushes up a pile of water, and the pile creates a wave. The wave moves and keeps on moving, carrying energy far from the place where the wave was created. Waves at the coast are frequently an indicator of a distant storm. But the water from that distant storm didn't move very far, just the wave. The wind pushed the water and the water pushed other water and the energy traveled for thousands of miles, even though the water only moved a few feet.

You can make waves on a rope or the toy called a "slinky." (If you've never played with a slinky, you should go to a toy store as soon as possible and buy one.) Take a long rope, stretch it across a room, shake one end, and watch the wave move all the way to the other end – and then bounce back. (Water waves, when they hit a cliff, also bounce.) The rope jiggles, but no part of it moves very far. Yet the wave does, with remarkable speed.

Sound is also a wave. When your vocal cords vibrate, they shake the air. The air doesn't move very far, but the shaking does, as far as the ear can hear (and further). If it hits a wall, it bounces. That's what gives rise to echoes. Sound waves bounce, just like water waves and rope waves.

A remarkable thing about all these kinds of waves is that the shaking leaves the location where it started. Shake some air and you create a sound, but the sound doesn't stay around. A wave is a way of transporting energy long distances, without actually transporting matter. It is also a good way to send a signal.

It turns out that light, radio, and TV signals also consist of waves. We'll get to that in the next chapter. What is waving for these? The traditional answer is "nothing" but that is really misleading. A much better answer is "the vacuum." We'll discuss this further in the chapter on quantum mechanics.[1]

wave packets and quantum mechanics

Waves can be long, consisting of many vibrations, as when you hum, or they can be short, as in a shout. Have you noticed that short waves act in a way very similar to particles? They move and they bounce. They carry energy, just as a moving particle carries kinetic energy. In fact, the theory of quantum mechanics is really a fancy name for the theory that all particles are really little packets of waves. The packets for an electron and proton are so small that we don't normally see them. What is waving in an electron? We think it is the same thing that is waving for light: the vacuum.

[1] Here is a brief summary of the answer: when they discovered that light was a wave, physicists didn't know what was waving, but they gave it a name: "Aether." (I spell it this way to distinguish it from the chemical "ether" which is totally different.) Most modern physicists believe that Aether was shown not to exist, but that isn't true. The distinguished theoretical physicist Eyvind Wichmann points out that the Aether was only shown to be invariant under the laws of Special Relativity, and therefore was unnecessary. But then quantum mechanics started giving it properties (it can be polarized; it carries dark energy). Wichmann says that the Aether never went away from physics; it was made more complex, and simply renamed the *vacuum*.

So when we are studying sound, water, and earthquakes, you are really learning the properties of waves, and that will be most of what you need to understand quantum mechanics.

Sound

Sound in air results when air is suddenly compressed, for example from a moving surface (e.g. vocal cord or bell). The compression pushes against adjacent air, and that pushes against the air in front of it, and so on. The amazing thing about sound is that the disturbance travels, and the shaking of the original air stops. The energy is carried away very effectively.

The motion of air molecules in a sound wave is illustrated in the animated image below.

A wave that behaves just like sound can travel in rock, water, or metal. This kind of sound is generated whenever anything is suddenly compressed. Hit a hammer on a railroad rail. The metal rail is momentarily distorted. The distortion will travel down the rail. If someone puts their ear to the rail, a mile away, they will hear the sound as it passes them.

Because steel is so stiff, it turns out that sound travels 18 times faster in steel than in air. In air, sound takes 5 seconds to go one mile; in steel, sound will go that same distance in less than 1/3 second. In the olden days, when people lived near railroad tracks, they could listen to the track to hear a train was coming, and they could even estimate the distance to the train by the loudness of the sound.

For sound to travel, the molecules of air have to hit other molecules of air. That's why the speed of sound is approximately equal to the sound of molecules. We discussed this fact in Chapter 2. But in steel, the molecules are already touching each other. That's why sound in steel can move much faster.

Sound travels in any material that is springy, i.e. which will return to its original shape when suddenly compressed. The speed of sound in water is about 1 mile per second, but it varies slightly depending on the temperature and depth of the water. Note that sound in water is a different kind of wave than the water wave that moves on the surface. The surface water wave may be a few inches or a few feet high. In water, sound travels under the surface, in the bulk of the water.

A surprising but remarkable fact: The speed of sound in air doesn't depend on how hard you push; it depends only on the properties of the material being pushed! No matter how loud you shout, the sound doesn't get there any faster.

Why is that? Remember, at least for air, the speed of sound is approximately the speed of molecules. The signal has to go from one molecule to the next, and it can't do that until the air molecule moves from one location to another.

But the speed of sound does depend on the temperature of the air. That's because the speed depends on the velocity of the air molecules, and when air is warmer, it is greater.

The table below gives the speed of sound in several materials:

material and temperature	speed of sound in that material
air at 0 C = 32 F	331 meters/sec = 1 mile every 5 seconds
air at 20 C = 68 F	343 meters/sec
water at 0 C	1402 m/sec = 1.4 km/sec
water at 20C	1482 m/sec = almost 1 mile per second
steel	5790 m/sec = 3.6 miles per second
granite	5800 m/sec

Sound traveling in rock gives us very interesting information about distant earthquakes. We'll come back to later in this chapter. Measurements of the surface of the sun show sound waves arriving from the other side. Sound has been detected traveling through the moon, created by meteorites hitting the opposite side.

There is no sound in space because there is nothing to shake. A famous tag line from the science fiction movie "Alien" was: "In space, nobody can hear you scream." Astronauts on the moon had to talk to each other using radios. Science fiction movies that show rockets roaring by are not giving the sound that you would hear if you were watching from a distance – since there would be no sound.[2]

Transverse and longitudinal waves

When you shake a rope, the wave travels down its length – but the shaking is sideways, i.e. the rope vibrates sideways even thought the location of the shaking travels along the rope. This kind of wave is called a "transverse" wave. In a transverse wave, the motion of the particles is along a line that is perpendicular to the direction the wave is moving.

A sound wave is different. The vibration of the air molecules is back and forth, in the same direction that the wave is moving. Such a compressional wave is called a "longitudinal wave." In this wave, the motion and direction of the wave are along the same line.

Ordinary (surface) water waves are peculiar. If you are floating on the water, and a wave passes by, you will move up and down and also back and forth (along the direction of the

[2] To enjoy the movie, I always assume that the microphone is located on the spacecraft, so although we are watching the rocket pass, we are hearing sound as if we were on the rocket.

wave motion). In fact, for small water waves, your motion will be in a circle! The water below the surface also moves, but in a smaller circle. Thus water waves are both transverse and longitudinal.

Note that surface water waves are quite different from water sound waves. They travel slower (typically one meter per second, vs. 1.4 km/sec). They are circular, rather than purely longitudinal. And, of course, whereas the ordinary water waves travel on the surface, the sound waves travel in the bulk of the water, beneath the surface. In fact, sound waves, when they come up from below and reach the surface, will bounce off the surface and go back down, just as if they were bouncing off a wall.

Water waves

Water waves (the term we will use when we mean the ordinary surface water waves – as opposed to water sound waves) are the what gave waves their name. If you swim or float and a water wave passes by, you move slightly back and forth as well as up and down. It is worth while going to swim in the ocean just to sense this. In fact, for most water waves, the sideways motion is just as big as the up and down, and you wind up moving in a circle! But when the wave is past, you (and the water around you) are left in the same place. The wave, and the energy it carries, passed by you.

When there is a series of waves following each other, we call that a wave packet. The distance between the crests (the high points of the waves) is called the wavelength. Waves with different wavelengths travel at very different speeds. Those with a short wavelength go slower, and those with a long wavelength go faster. In deep water (when the depth is greater than the wavelength), the equation is[3]:

$$v \approx \mathrm{sqrt}(L)$$

In this equation, v is the velocity in meters per second, and L is the wavelength in meters, and the in the second equation, ≈ means "approximately equal to." So, for example, if the wavelength (distance between crests) is 1 meter, then the velocity is about 1 meter per second. If the wavelength is 9 meters, the velocity is 3 meters per second. Does that agree with your image of ocean waves? Next time you swim in the ocean, check it. Long waves move faster.

That equation is remarkably simple, but it is correct only for deep water, that is, for water that is much deeper than a wavelength.

[3] The standard physics equation for deep water waves is $v = \mathrm{sqrt}(gL/(2\pi))$, where $g = 9.8$ m/sec^2 is the acceleration of gravity (from Chapter 3). Putting in $g = 9.8$, gives $v \approx 1.2\ \mathrm{sqrt(L)} \approx \mathrm{sqrt(L)}$.

Shallow water waves

*** note from Justin: clarify which parts are only for water and which are for all waves (e.g. v = f L).
When the water is shallow (the depth D is much less than the wavelength L) then the equation changes:

$$v = 3.13 \text{ sqrt}(D)$$
$$\approx \pi \text{ sqrt}(D)$$

where D is the depth in meters.[4] Note that all shallow water waves travel at the same velocity, regardless of their wavelength. Their speed depends only on the depth of the water. This might match your experience when you surf on relatively long waves in shallow water.

If the wavelength is very long, then we have to consider even the deep ocean to be shallow. This is often the case for tsunamis.

Tsunamis (Tidal Waves)

A tsunami is a giant wave that hits the coast and washes far up on the shore, often destroying buildings that are within a few hundred meters of the beach. Tsunamis were traditionally called “tidal waves,” but a few decades ago scientists (and newspapers) decided to adopt the Japanese word, and now it is more commonly used.

Underwater earthquakes and landslides often generate tsunamis. These waves often have a very high velocity and a very long wavelength. In the deep ocean, they may have a very low amplitude, so they can travel right under a ship without anyone on board even noticing. But as they approach land, they are slowed down, and the energy is carried by a smaller depth of water -- so their amplitude rises. The rise can be enormous, and that is what causes the damage near the coast.

In Pacific islands (such as Hawaii) you’ll see sirens mounted on poles near the beaches. If an earthquake is generated within a few thousand miles, these sirens will be sounded to warn the residents to evacuate. A tsunami could arrive within a few hours.

If a very large earthquake fault moves underneath deep water, the wave it creates can be very long. For a large tsunami, a typical wavelength is 10 km, some have been seen with wavelengths of 100 km and more. That means even in water whose depth is 1 km = 1000 meters, a tsunami is a *shallow* water wave! (Recall that a “shallow water wave” is one in which the wavelength is greater than the depth.)

[4] The second equation is only approximate. I wrote it using the symbol π to make it easier to remember – but that is optional. You don’t have to remember it.

The velocity of the tsunami can be calculated from the shallow water equation. In water 1 km deep, D = 1000, so the velocity is v = 3.13 sqrt(1000) ≈ 100 meters/sec. That's 1 km in 10 seconds -- very fast. A tsunami that is generated by an earthquake 1000 km away will take 10,000 seconds to arrive, just under three hours.

Imagine a tsunami with that velocity, with a wavelength of 10 km. Even at its high velocity of 100 meters per second, it will take 100 seconds after one crest passes you before the next one arrives. The water will fall for the first 50 of these seconds, and then rise for the next fifty. Thus, although these waves travel fast, they are slow to rise and fall. That's why tsunamis were called tidal waves. If you are in a harbor, and there is a small tsunami, it might take 100 seconds for the water to rise and fall, and it gives the appearance of a tide. The image of a huge breaking wave hitting the shore is largely fiction; most tsunamis are just very high tides that come and wash away everything close to the shore.[5] That's how they do their damage. If the ocean rises 10 meters, it destroys everything, even if it takes 50 seconds to reach its peak. If you are young and healthy, you can usually outrun the rising water as it comes in. If you are not fast enough, then you get swept up in a very large volume of water, and dragged out to sea when the wave recedes. Small tidal waves are frequently observed as slow (100 second) rises and falls in harbors. Boats tied to docks are often damaged by these slow waves as they rise above the dock and get thrown into other boats. Many captains take their boats out into the harbor or out to sea when they are alerted that a tsunami is coming. The word *tsunami*, in Japanese, means *harbor wave*.

Sound -- doesn't always travel straight

Sound waves, whether in air in ocean, often do not travel in straight lines. They will bend upwards or downwards, to the left or to the right, depending on the relative sound speed in the nearby material. Here is the key rule:

> **Waves tend to change their direction by bending their motion towards the side that has a slower wave velocity.**

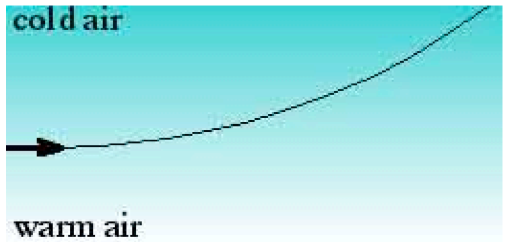
To understand why this is so, imagine that you are walking arm in arm with a friend. If your friend is on your left side, and slows down, that pulls your left side backwards, and turns you towards the left. If your friend speeds up, that pulls your left arm forward, and turns you to the right (and also turns your friend to the right). The same phenomena happens with waves. A more complete description of this is given in the optional section at the end of the chapter.

[5] The tsunami in the movie "Deep Impact" is particularly inaccurate. It shows a giant wave breaking over Manhattan island. But the harbor of New York City is relatively shallow; there is no place for that much water to come from, unless a giant wave broke far out to sea.

This rule is true for all kinds of waves, including sound, water surface waves, and even earthquakes and light.

example: "normal atmosphere"

Here is an example from the atmosphere. At high altitude, the air is usually colder. Imagine a sound wave that is initially traveling horizontally, near the surface of the earth. Above it, the velocity is lower, so it will tend to bend upward. This is shown in the following diagram.

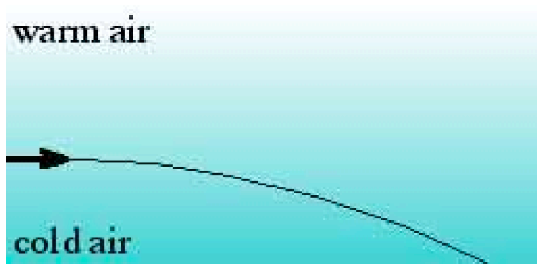


normal atmosphere near ground

Notice that the sound bends away from the ground towards higher altitude. It bends upward. That's because the air above it has a slower sound velocity (it is colder).

Sound in the evening

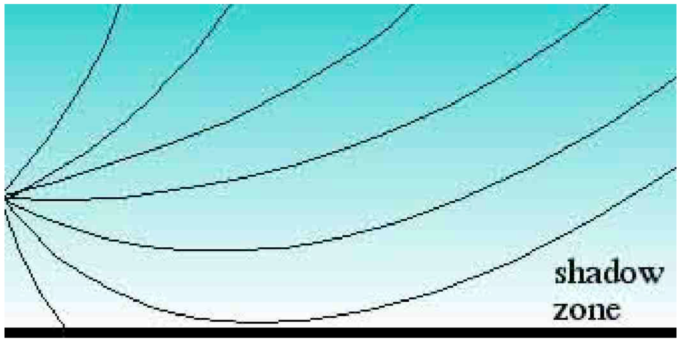
When the sun sets, the ground cools off rapidly. (It does this by emitting infrared radiation; we'll discuss this further in the chapter on "invisible light".) The air does not cool so quickly, so in the evening, the air near the ground is often cooler than it is up higher. This phenomena is called a "temperature inversion." Sound tends to bend down towards the ground, as shown in the following figure.



sound near ground when there is an inversion

Sound during the day, again

Now let's look at the morning situation again, with warm air near the ground, and cold air up high. But let's draw many sound paths, all coming from the same point. This is done in the diagram below.

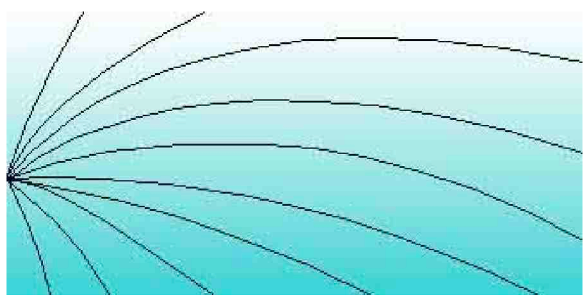


The solid line at the bottom represents the ground. Note that it blocks certain paths -- the ones that drop too steeply. In the lower right corner is a small region that none of the paths can reach, since to reach this region the sound waves would have to go through the ground. (We'll assume for now that the ground absorbs or reflects sound, and does not transmit it, at least, not very well.) If the sound were coming from the point on the left, and you were standing in the shadow zone, then you wouldn't hear any sound at all. You are in the sound shadow of the ground!

This diagram shows why mornings tend to be quiet. Sounds bend up towards the sky, and if you are near the ground, there is no way that most of them can reach you.

Sound in the evening

In the diagram below, I've redrawn the evening situation, with the inverted temperature profile (cold at the bottom, warm at the top).



Note that there is no shadow zone. No matter where you stand, there are paths by which the sound can reach you.

Have you ever noticed that you can hear more distant sounds in the evening than in the morning? I've noticed that in the evening I can often hear the sound of distant traffic, or of a train; I rarely hear such sounds in the morning. (This phenomenon first mystified me when I was a teenager, living 1/4 mile from the beach. I noticed that I could hear the waves breaking in the evening, but almost never in the morning.)

The explanation is in the diagrams above: in the morning there is a shadow zone for most sound, and if I am near the ground, then many sounds can't reach me; they are bent up to the sky. But in the evening, sound that is emitted upward bends back down, and you can hear sound from distant places.

Predicting a hot day

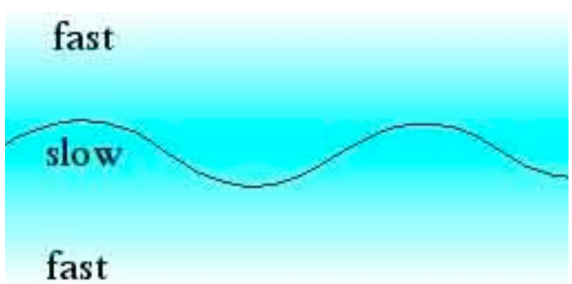
There are times when I wake up in the morning and hear distant traffic. Then I know that it will probably be a hot (and maybe smoggy) day. Why?

The reason is that hearing distant sounds means there is an inversion, i.e. the high air is warmer than the low air. The sound diagram is identical to the sound diagram show above for the evening.

The presence of an inversion in the morning leads to a special weather condition, because it means that as the air near the ground warms, it will not rise. Normally, hot air rises into cold air, since hot air is less dense. But if there is hot air above, that kind of convection doesn't take place. With no place to rise to, the hot air accumulates near the ground, making for a hot day. Smog and other pollutants also accumulate. The weather forecast on the radio or TV will often announce that there is an "inversion". Now you know what that means: that the normal temperature profile is inverted, i.e. it is upside-down with the cool air near the ground.

Focusing sound: the sound channel explained

In the ocean, the temperature of the water gets cooler as we go further down. This would make the speed of sound less. But, as mentioned earlier, the water is also getting more and more compressed (i.e. denser) because of the increasing pressure. This tends to make sound go faster. When these two effects are combined, we get a gradual decrease in sound velocity as we go from the surface to about 1 km depth, and then the sound velocity increases again. This is illustrated in the diagram below. Darker means slower sound (just as it did in the atmosphere diagrams).



I've also drawn the path of a ray of sound. Notice that it always bends towards the slow region. The path I drew started with an upward tilt, was bent downward, passed through the slow region, and then was bent upward. The path oscillates up and down, but never gets very far from the slow region, the 1 km-deep "sound channel".

Exercise: Draw some other paths, starting at different angles. What happens if the ray starts out horizontally? Vertically?

How sofar saved downed pilots

Let's return now to the magic of Ewing's Sofar spheres. As I stated earlier, they were hollow, and yet they were made of heavy material. Since they weighed more than an equal volume of water, they didn't float, but sank. Ewing designed the spheres to be strong enough to withstand the pressure of water down to a depth of 1000 meters. At this depth, the spheres were suddenly crushed. (Like an egg, the round surface provides lots of strength, but when it breaks, it breaks suddenly.) The water and metal collapsed, and bang against the material coming in from the other side. It's like a hammer hitting a hammer, and it generates a loud sound. The energy released from a sphere with radius 1-inch at a depth of 1 km, is approximately the same as in 60 milligrams of TNT. That doesn't sound like a lot -- but it is about the same you might find in a very large firecracker.

In the air, the sound of a firecracker doesn't go far, perhaps a few kilometers. But at a depth of 1000 meters, the ocean sound channel focuses the sound. Moreover, the sound channel is quiet. Only sounds generated in the sound channel itself are carried. Sound created in the sound channel stay in the sound channel, so it doesn't spread out as much as it would otherwise. Microphones placed within the sound channel can hear sounds that come from thousands of kilometers away.

During World War II, the Navy had arranged for several such microphones placed at important locations, where they could pick up the ping of the imploding Ewing spheres. They could locate where the implosion had taken place by the time of arrival of the sound. If the sound arrived simultaneously at two microphones (for example), then they knew the sound had been generated somewhere on a line that is equally distant from the two microphones. With another set of microphones they could draw another line, and the intersection of the two lines gave the location of the downed pilot.

Historical note: Sofar supposedly stands for "**So**und **f**ixing **a**nd **r**anging." Fixing and ranging was Navy terminology for determining the direction to a source (that's the fixing part) and its distance (ranging). Despite all this, I suspect that the acronym was forced, and the real name came about because the channel enabled you to hear things that were *so far* away. Some people still refer to the sound channel as the sofar channel. I learned about the sofar spheres from Luis Alvarez, who knew about them from his scientific work during World War II. I have spoken to several other people who remember them, including Walter Munk and Robert C. Spindel. Spindel believes that the spheres contained a small explosive charge to enhance the sound. We have not yet found any historical documentation that verifies this.

Whale songs

What does the sound channel look like? The word "channel" can be misleading, since it brings up a vision of a narrow corridor. It is not like a tube. It is a flat layer, existing about a kilometer deep, spreading over most of the ocean. Sound that is emitted in the sound channel tends to stay in the sound channel. It still spreads out, but not nearly as much as it would if it also spread vertically. That's why it can be heard so far. It tends to get focused and trapped in that sheet.

In fact, the sound channel is like one floor in a very large building, with ceiling and floor but without walls. Sound travels horizontally, but not vertically. If sound is emitted at the surface of the ocean, then it does not get trapped. So the sound of waves and ships doesn't pollute the sound channel. The sound channel is a quiet place for listening to sofar spheres, and other sounds that were generate in the sound channel.

Whales discovered this, probably millions of years ago. We now know that whales like to sing when they are at the sound channel depth. These songs are hauntingly beautiful. If your computer has the right software, you can listen here to the recorded song of the humpback whale and of the gray whale. You can find other recordings on the web, and you can buy recordings on CDs.

Global Positioning System (GPS)

A favorite gift for hikers, boaters, and travelers is a Global Positioning System (GPS for short) receiver. This is a small device that will tell you where you are on the earth, to an accuracy of a few feet. You can buy one at a sporting goods store for about $100. If you rent a car, for a small charge you can get one with GPS built in -- to help keep you from getting lost.

Why am I talking about GPS? Because GPS uses the same idea that Maurice Ewing used for locating pilots. For GPS, however, the signals are sent using radio waves rather than sound. And instead of using microphones set on the edges of the ocean, it uses radio receivers orbiting the Earth.

The GPS system works because there are a large number of satellites in space that are emitting signals. Each signal contains the time when it was emitted, and the position of the satellite when it was emitted. The GPS also has a small computer, and an accurate clock.

When the GPS receiver receives a signal, it looks at the time, reads the message saying when the signal was emitted, and determines how long the signal was traveling. It multiplies that by the speed of light, and that gives it the distance to the first satellite. Of course, it also knows exactly where that satellite was when it emitted the signal. Once the GPS knows its distance from three different satellites, it can use geometry to calculate where it is. Can you see why that works?

GPS Geometry

How does the GPS system get its location by knowing the distance to three satellites? It's easy to see by analogy. Suppose you didn't know where you were in the US, but knew that you were 1000 miles from Denver, and 1500 miles from San Francisco. You could get a map, draw a circle around Denver with a 1000 mile radius; then draw a 1500 mile circle around San Francisco. The circles intersect at two points. If you knew your distance to one other city, you would know which of those two points was your location.

If the GPS receiver gets a signal from four satellites, then it can see if the distance to that satellite is exactly what it expected. It should come out right -- since the GPS already knows its own position. Suppose it turns out to be wrong? The only explanation can be that the clock in your inexpensive GPS receiver has drifted and is no longer accurate. So the receiver can use the 4th satellite to fix its clock! The result is that if it can pick up 4 satellites, the receiver does not need an accurate clock.

The Cold War -- and SOSUS

During World War II, the part of the military that used submarines was called "The Silent Service." This reflected the fact that any sound emitted by a submarine could put it in danger, so submariners trained themselves to be very quiet. Someone in a sub who drops a wrench makes a sound that is unlike any other in the ocean. Fish don't drop wrenches. The wrench clatters against the hull, and the hull carries the sound to the water, and the vibrations of the hull send the sound into the ocean. Ships on the surface, and other submarines, had sensitive microphones to listen to possible sounds emitted from submarines.

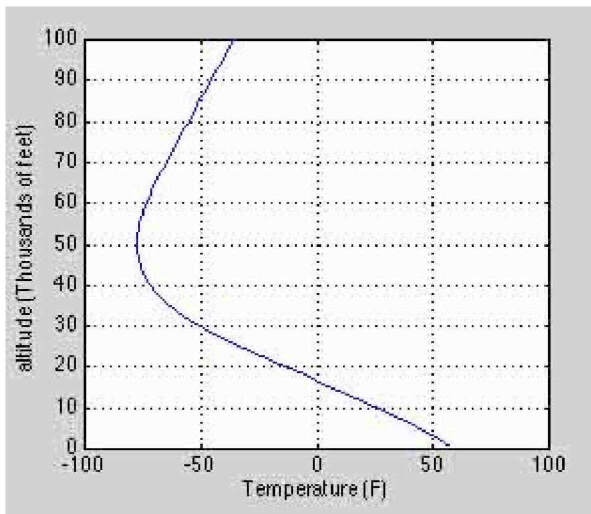
The presence of the sound channel did not remain secret for long, but its properties did. In the period from the 1950s to 1990s, the United States spent billions of dollars to put hundreds of microphones into the channel at locations all around the world, to carry the signals back to an analysis center, and then use the world's best computers to analyze them. The system was called SOSUS, an acronym for "SOund SUrveillance System." The magnitude of the SOSUS effort was one of the best-kept secrets of the Cold War. Effective use of SOSUS required the Navy to make extensive measurements of the ocean and its properties, and to update the temperature profile of the ocean all around the world. (The ocean has weather fronts analogous to those in the atmosphere.)

Optional: Book to read If you really want to know more about this subject, one of the best introductions is the novel "The Hunt for Red October" by Tom Clancy. When this novel came out in 1984, much of the material in it was still classified. Clancy had a talent for reading documents, talking to people, and figuring out from what they said, what was really true. The book was so detailed, and so accurate (it does have some fiction in it too -- and some things that he got wrong) that new people joining the Submarine service were told to read the book in order to get a good picture of how operations worked! Many of the details of the SOSUS system were finally declassified in 1991, seven years after Clancy's book was published.

Back to UFOs: a sound channel in the atmosphere?

Soon after he did his work in the ocean, Maurice Ewing realized that there would be a sound channel in the atmosphere! His reasoning was simple: as you go higher, everyone knows the air gets colder. Mountain air is colder than sea level air. The temperature of the air drops about 4 degrees Fahrenheit for every 1000 feet of altitude gain.

That means that the velocity of sound decreases with altitude. But he also knew that when you get to very high altitudes, the temperature begins to rise again. Starting at about 40-50,000 ft, the air starts getting warmer. This is shown in the following figure:



Remember that the speed of sound depends on the temperature of the air. When the temperature is low, so is the speed of sound. That means that the speed of sound is fast at both high and low altitudes, and slower at about 50,000 ft.

Look at the diagram above the previous one, the diagram that showed sound moving in a wiggly line through the ocean. Exactly the same diagram can be used for sound in the atmosphere. That means that there is a sound channel in the atmosphere, centered at about 50,000 feet. (The exact altitude depends on latitude, as well as on the season of the year.) This is what Ewing figured out. He had an important US National Security application in mind to take advantage of this realization.

But first, a little more physics. Why does the atmosphere get warmer above 50,000 ft?

Ozone: the cause of the high altitude heating

Why does the air get warm at very high altitude? The reason is the famous ozone layer. At about 40-50,000 feet, there is an excess of ozone, and this ozone absorbs much of the ultraviolet radiation from the sun. Ultraviolet is that part of sunlight that is more violet than violet. This light is there, but invisible to the human eye. The ozone layer protects us, since ultraviolet light when absorbed on the skin can induce cancer. We'll talk more about the ultraviolet radiation in Chapter 9 on "invisible light."

At the end of the 20th century, scientists began to fear that the ozone layer could be destroyed by human activity, and that would let the cancer-causing ultraviolet radiation reach the ground with greater intensity. In particular, they worried about the release of certain chemicals into the atmosphere (CFCs, an abbreviation for "chloro-fluoro-carbons", a chemical used in refrigerators and air conditioners). CFCs release fluorine, and fluorine catalyzes the conversion of ozone O_3 into ordinary O_2. (To balance the equation, 2 molecules of O_3 turn into 3 molecules of O_2.)

The use of CFCs was outlawed internationally, and this is expected to solve the problem. For this reason, the human destruction of the ozone layer is no longer considered an urgent problem.

Looking at the ozone layer (and the sound channel): thunderhead tops

On a day where there are large thunderstorms, you can see where the ozone layer is: right at the top of the tallest thunderheads. A thunderstorm grows from hot air at the ground, rising up through the colder (and denser) air above it. When the warm air hits the warm air of the ozone layer, it no longer rises. The cloud spreads out, making the "anvil head" shape that people associate with the biggest storms. So when you see the flat top of a large thunderhead cloud, you are looking at the ozone layer, and at the middle of the sound channel.

Figure: Image of an "anvil head" thunderstorm.
The ozone layer (and the sound channel) is at the top of the cloud.
(image is in the public domain. It was taken from http://www.photolib.noaa.gov/historic/nws/images/big/wea00031.jpg)

Ewing’s Project Mogul and his flying disks

Maurice Ewing had an urgent application for his predicted atmospheric sound channel: the detection of nuclear tests in Russia. In the late 1940s, the "Cold War" had begun, and there was growing fear of the totalitarian communism represented by Russia. They had great scientists, and there was widespread belief that they would be building an atomic bomb soon. At that time, Russia was a very secret and closed society. In fact, Stalin was starving 30 million "Kulak" farmers, and he could get away with it because he controlled information going in and out. In 1948, George Orwell wrote "1984", expressing his fears of such a government.

Ewing realized that as the fireball from a nuclear explosion rose through the atmospheric sound channel, it would generate a great deal of noise that would travel around the world in the channel. (*** not all the bang is on the ground. The fireball continues to generate sound.) He argued that we should send microphones up into the sound channel to detect and measure any such sound. The microphones that he used were called "disk microphones". You can see them in photographs of old radio shows. Click for an old photo of a disk microphone. There is also a photograph of a somewhat smaller disk microphone used by Orson Wells in his famous 1938 broadcast of the "War of the Worlds", when he actually convinced many listeners that the world was under attack by Martians!

Ewing's idea was to string the microphones under a high-altitude balloon, have them pick up the sounds in the sound channel, and radio them back to the ground. The disk microphones were called "flying disks." (The word flying was not confined to airplanes; it was equally used by ballooners when they went up.) The balloons were huge, and the string of microphones was 657 feet long, longer than the Washington Monument is high: see the diagram of Project Mogul and the Eiffel Tower.
The project was a success. The system detected American nuclear explosions, and then, on August 29, 1949, it detected the first Russian test.

The Roswell crash of 1947

One of the Project Mogul balloon flights crashed near the Roswell Army Air Force base on July 7, 1947. It was recovered by the Army, who issued a press release stating that "flying disks had been recovered." The Roswell Daily Record had headlines the next day. We referred to these at the beginning of this chapter: RAAF Captures Flying Saucer.

It was not a flying saucer; it was a complex balloon project that carried flying disks -- microphones to pick up Russian nuclear explosions. The program was highly classified, and the press release said more than the security people considered acceptable, so the next day the press release was "retracted." A new press release stated that what had crashed was a "weather balloon." It wasn't a weather balloon. The US Government was lying.

discussion question: should the US Government ever lie? This is just the sort of issue that you should confront *before* you become president!

The government finally tells the truth

In 1994, at the request of a congressman, the U.S. government declassified the information they had on the Roswell incident, and prepared a report
Documents available for you to read are:
New York Times article published after the US Government report was released
Popular Science article published in June 1997, describing the Government report. html or pdf versions are available.
Popular Science follow-up article, September 1997. pdf version only.
Official US Government report (synopsis only) on Project Mogul
Official US Government report on the Roswell Incident
Of these articles, you should read at least the New York Times article. The Popular Science articles give interesting background. The Official US Government report gives details that some of you might find interesting.

How do we know the government isn't lying now?

Many people believe the official government report on Project Mogul is just an elaborate cover-up. They believe that a flying saucer really did crash, and the government doesn't want the public to know. Maybe I am part of this conspiracy, and part of my job is to mislead you into believing that flying saucers don't exist! (According to the movie "Men in Black", the job of the Men in Black is to make sure the public never finds out.)

I suggest the following answer: the people who continue to believe that Project Mogul never happened, probably don't understand the remarkable science of the ocean and atmosphere sound channels. I could not have invented such a wonderful story. It has too many amazing details. In contrast, it is relatively easy to make up stories about flying saucers. Those don't require much imagination. So here is my hypothesis: it is possible to distinguish the truth by the fact that it is more fascinating!

Of course, I might be lying.

Earthquakes

When a fault in the Earth suddenly releases energy, it creates a wave in the ground. The location where the earthquake started is called the "epicenter." Most people who have experienced an earthquake were far from the epicenter, and were shaken by the wave that started at the epicenter and shook them as it passed by.

The epicenter can be located by noting when the earthquake wave arrived at several different locations -- just as the SOFAR system was used to located downed pilots in World War II. Moreover, the epicenter is often deep underground, so even someone who is standing at the latitude and longitude of the epicenter can be standing over 50 miles away from it (i.e. above it).[6]

Huge amounts of energy are released in earthquakes, often greater than in our largest atomic weapons. That shouldn't surprise you. If you are making mountains shake over distances of tens or hundreds of miles, it takes a lot of energy. In 1935, Charles Richter found a way to estimate the energy from the measured shaking. His scale, originally called the "Magnitude Local", became known as the "Richter scale." An earthquake with Magnitude 6 is believed to release the energy equivalent of about 1 million tons of TNT. That is the energy of a medium-size nuclear weapon. Go up one magnitude to Magnitude 7 (roughly the size of the Loma Prieta earthquake that shook San Francisco and the World Series in 1989) and the earthquake releases an energy 10 to 30 times greater.

Why do I say a factor of 10 to 30? Which is it? The answer is: we don't really know. Magnitude is not exactly equivalent to energy. For some earthquakes, a magnitude difference of 1 unit will be a factor of 10, and for others it will be a factor of 30. It is easier to determine magnitude than it is to determine energy, and that's why magnitude is so widely used.

In the table below I give the approximate magnitudes of some historical earthquakes in the US.

Earthquake	approximate magnitude	megatons of TNT
	6	1
San Francisco area 1989	7	10 to 30
San Francisco 1906	8	100 to 1000
Alaska 1999	8	100 to 1000
Alaska 1964	9	1000 to 30,000
New Madrid Missouri 1811	9	1000 to 30,000

Waves transport energy from one location to another. The velocity of an earthquake wave depends on many things, including the nature of the rock or soil in which it is traveling (granite? limestone?), and its temperature (particularly for earthquakes traveling in deep rock).

A particularly deadly effect occurs when a wave moves from high velocity material such as rock into low velocity material such as soil. When a wave slows down, its wavelength -- the spacing between adjacent crests -- decreases. But the energy is still there, but now squeezed into a shorter distance. That increases the amplitude of the shaking. Even though the energy carried by the wave is unchanged, the effect on buildings becomes much stronger. This is what happened in downtown Oakland in the 1989 Loma Prieta

[6] "Shallow" earthquakes are defined to be those less than 70 km deep. See: http://neic.usgs.gov/neis/general/handouts/depth.html

quake. The earthquake wave passed right through much of Oakland without causing great damage, until it reached the area near the freeway. This region had once been part of the bay, and had been filled in. Such soft ground has a slow wave velocity, so the amplitude of the earthquake increased when it reaches this ground. The most dangerous areas in an earthquake are regions of landfill. The marina district in San Francisco was also landfill, and that is why it was so extensively damaged.

Personal story from the author: My daughters were at the Berkeley WMCA when the 1989 Loma Prieta earthquake hit. One of them told me that she was thrown up against the wall by the earthquake. I said to her, “No, Betsy, that was an illusion. You weren’t thrown against the wall. The wall came over and hit you.”

Measuring the epicenter of an earthquake

You already know that you can measure the distance to a lightning flash by counting the seconds and dividing by five. The result is the distance to the lightning in miles. But here is another trick: as soon as you feel the ground shaking, and as you are ducking for cover, start counting seconds. When the bigger shaking finally arrives, take the number of seconds and *multiply* by 5. That will give you the distance to the epicenter (the place where the earthquake started) in miles.

Why does that work? To understand it, you should know that in rock, there are three important kinds of seismic waves. These are:

The P wave
(primary, pressure, push)

P stands for "primary" because this wave arrives first. This is a longitudinal (compressional) wave (as is ordinary sound). That means that the shaking is back and forth in the same direction as the direction of propagation. So, for example, if you see that the lamppost is shaking in the East-West direction, that means that the P wave is coming from either the East or the West. Some people like to use the memory trick that the P wave is a Pressure wave -- i.e. it is like sound, in being a compression and rarefaction, rather than a transverse motion. The P wave travels at about 6 km/sec = 3.7 miles per second. That is a lot faster than the speed of sound (which is 300 meters per second = 0.3 km/sec).

The S wave
(secondary, shear)

S stands for "secondary" because this wave arrives second. This is a transverse wave. That means that the shaking is perpendicular to the direction of propagation. If the wave is traveling from the East, then this implies that the shaking is either North-South, Up-Down, or somewhere in between. Some people like to use the memory trick that the S wave is a Shear wave -- i.e. it can only propagate in a stiff material which does not allow easy shear motion (i.e. sideways slipping). Liquids do not carry shear waves. The way that we know that there is a liquid core near the center of the Earth is because shear waves do not go through it. The S wave travels at about 3.5 km/sec = 2.2 miles per second.

The L wave
(long, last, Love)

L stands for "long". (It also stands for Love, after A.E.H. Love, who worked out some of their properties in 1911.) These are waves that travel only on the surface of the Earth. Like water waves, they are a combination of compression and shear. They are created near the epicenter when the P and S waves reach the surface. They are called long because they tend to have the longest wavelength of the three kinds of seismic waves. It is the L wave that usually does the most damage, because the wave traveling on the surface often develops the biggest amplitude. The L wave travels at about 3.1 km/sec = 2 miles per second. Some people like to use the memory trick that the L wave is the Last to arrive. (Careful. The L wave is NOT a pure "Longitudinal" wave!)

To estimate the distance of the quake, as you are ducking under a table, start counting seconds from when you felt the first tremor, i.e. the P wave. (You can get very good at doing this if you live in California long enough.) When the S wave arrives (it is usually a little bigger), then you know that:

for every second, the epicenter is about 8.4 km = 5 miles away.

Thus if there is a five second gap between the two waves, the epicenter was 5x5 = 25 miles away. You may even be able to estimate the direction from the P wave shaking: the back and forth motion is in the same direction as the source. If we are lucky enough to have an earthquake during class, then you can watch me do this.

For those of you who like math: can you see how I got the value of 8.4? It is based on the P and S velocities. Hint: the distance a wave travels is equal to the (velocity) x (time). This calculation is optional (not required) and relegated to a footnote.[7]

There are small earthquake waves passing by all the time, just as there are small waves everywhere you look on the ocean surface. These waves are recorded, in Berkeley, at the UC Seismographic station. To see the waves recorded for the last few hours, look at the

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[7] Suppose an earthquake is at a distance d from where you are standing. The p-wave moves with a velocity v_P. The time it takes the wave to reach you is $T_P = d/v_P$. The s-wave moves with a velocity v_S. The time it takes to reach you is $T_S = d/v_S$. First you feel the p wave, and you start counting seconds. Then the s wave arrives. The time difference that you measured is $T = T_S - T_P$. According to our equations, this is $T = T_S - T_P = d/v_S - d/v_P = d(1/v_S - 1/v_P) = d(1/2.2 - 1/3.7) = d(0.184)$. Solving for d gives: $d = T/0.184 = 5.4\ T$. We approximate this as $d = 5\ T$.

recent UC Berkeley Seismograph record. This is an extremely interesting link to keep on your computer; it is something you can check any time you think you might have felt a quake. (Wait a little while before checking; the online plot is only updated every few minutes.) You'll see it there, even when it is not reported on the news. The quakes that occur every day in this region are also available on a map.

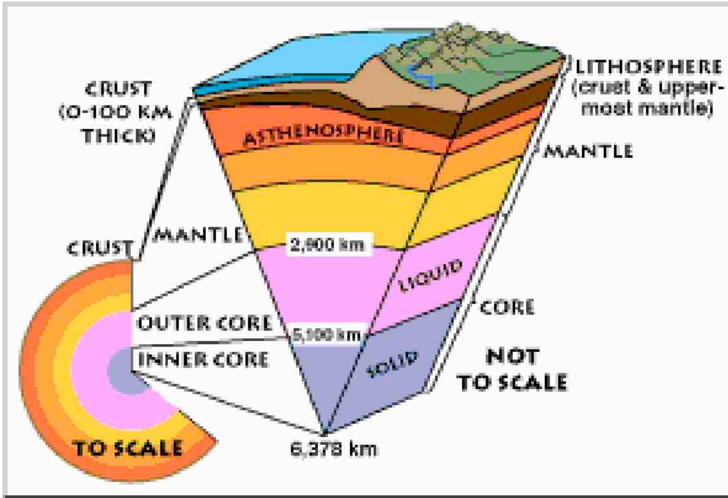
The liquid core of the Earth

Half way to the center of the Earth, about 2900 km deep (1800 miles) is a very thick layer of liquid. (The distance to the center of the Earth is 6378 km.) You could say that the entire earth is "floating" on this liquid layer. The layer is mostly liquid iron, and the flow of this liquid creates the Earth's magnetic field (as discussed in Chapter 6). So much for curious facts. But the real question for now is: how could we possibly know all this? The deepest we can drill is only a few miles. Nobody has ever gone to the core. Volcanoes don't come from regions that deep. How could we possibly know?

The interesting answer is that we know from watching signals from earthquakes. Thousands of these happen every year, and they are studied by earthquake detectors all around the Earth. The largest earthquakes send signals that actually travel down through the bulk of the Earth, and are detected on the opposite side.

An interesting aspect of the earthquakes that pass directly through the core is that only the P waves pass through. The S waves don't make it! That is the wonderful clue. P waves are longitudinal "pressure" waves, and they travel through rock, air, or liquids. But S waves are transverse "shear" waves. Shear waves travel through surfaces, but they don't go through liquids or gases. That's because a liquids and gases moving in the transverse direction can just slip past the rest of the liquid or gas; it doesn't exert much shear. So the fact that the P waves pass, but the S waves don't, gave one of the clues that there is a liquid core. Scientists also measured the speed with which the waves travel, and from this they can rule out many kinds of liquids. They measure the density of the core from its contribution to the mass of the Earth, and they also see the magnetic field that the core creates. From all this, they were able to rule out every possible liquid except iron, although there could be liquid nickel mixed in with it.

The image below shows the cross section of the Earth. Note that heights of the mountains are greatly exaggerated in this figure. The highest Mountain, Mt. Everest, is 29,035 ft high, which is about 8.8 km. That is a factor of 720 less than the distance to the center. If drawn to scale, the mountains would be less than the thickness of a line.



We believe that the iron melted on the Earth in the early days when the Earth first formed. Most of the iron sunk to the core, since it was more dense than the rest of the rock. It is still there, and it hasn't yet completely cooled off. The center of the core is under great pressure, and even though it is hot, it is solid.

Discussion question: how do we know the liquid core has a solid center? (Or rather, how did scientists figure that out?) For the answer, see the footnote.[8]

Bullwhips

In a bullwhip[9], the thickness of the whip is tapered towards the end. When the whip is snapped, a wave begins to travel down the whip to the end. Because the end is thin, the velocity of the wave increases near the end. The loud "crack" that you hear from the bullwhip is a "sonic boom" that occurs when the velocity of the waves exceeds the speed of sound.

Note the difference: In earthquakes and tsunamis, the added danger comes because the wave enters a region in which it slows. In the bullwhip, the crack comes because the wave speeds up.

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[8] When a compressional wave hits a certain depth (the depth of the inner solid core) it breaks up into two waves. From the behavior of these waves, we know that one of them is a shear wave. That implies that if we go to this depth, we once again run into solid material.

[9] If you don't know what a bullwhip is, then you might watch the opening scene in the movie "Raiders of the Lost Ark" in which Indiana Jones uses one with skill to take a gun out of the hand of a bad person.

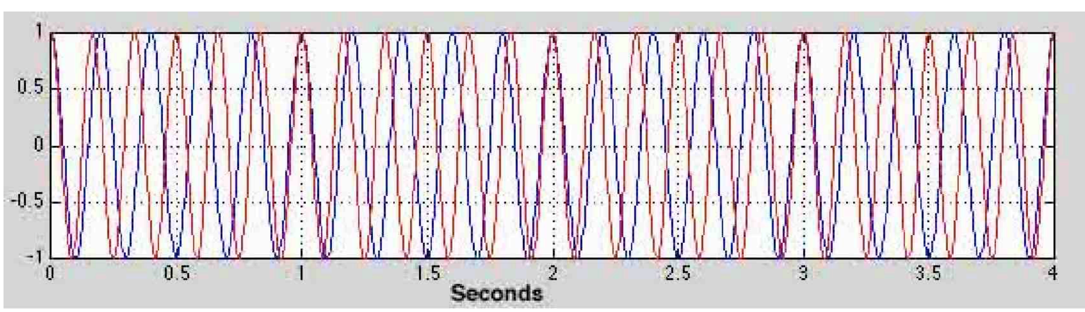
Waves can cancel (or reinforce)

Suppose you are very unlucky, and are standing right in the middle of two earthquakes. One is to the north, and it takes you up, down, up, down, up, down, etc. The other earthquake arrives from the south, and it shakes you down, up, down, up, down, up, etc., exactly the opposite of the shaking of the first wave. What will happen? Will the up from one be canceled by the down of the other?

The answer is yes! If you are unlucky enough to be between two such waves, then try to be lucky enough to be at just the right place for them to cancel. You are depending on the fact that the two waves arrive with exactly opposite amplitudes. Of course, if you were standing at a different location, the waves would arrive at different times, and they might not cancel. Suppose the first wave gave you up, down, up, down... and so did the second wave. Then the ups would arrive together, as well as the downs, and you would be shaken twice as much.

This cancellation of waves (or their addition) is extremely important. Since waves don't always travel in straight lines, you can even be hit by two different waves that originated from the same epicenter! If you are lucky, they will cancel, but a short distance away, they will add. This phenomenon was see in the 1989 Loma Prieta earthquake that shook Berkeley, Oakland, and San Francisco. There were buildings where one side was shaken badly (causing that side to fall down) and the other side was undamaged. This was probably due to the arrival of the wave from two directions at once, and the cancellation of the wave at the lucky end of the building.

Let's illustrate this with a figure. Take a look at the two different waves shown in the plot below, one in red and one in blue. The curves show the amount that the ground moves up and down, measured in centimeters, at different times, due to the red earthquake and the blue earthquake. Zero represents your original level. The blue earthquake shakes the ground upward (to 1 cm), and downward (to -1 cm). So does the red earthquake. So far we have not considered the effects when added together.



First look at the blue wave. At zero seconds, it starts at the maximum value of 1. It oscillates down and up, and by the time it reaches 1 second it has gone through 5 cycles. (Verify this. Try not to be distracted by the red wave.) We say that the frequency of the blue wave is 5 cycles per second = 5 Hertz.

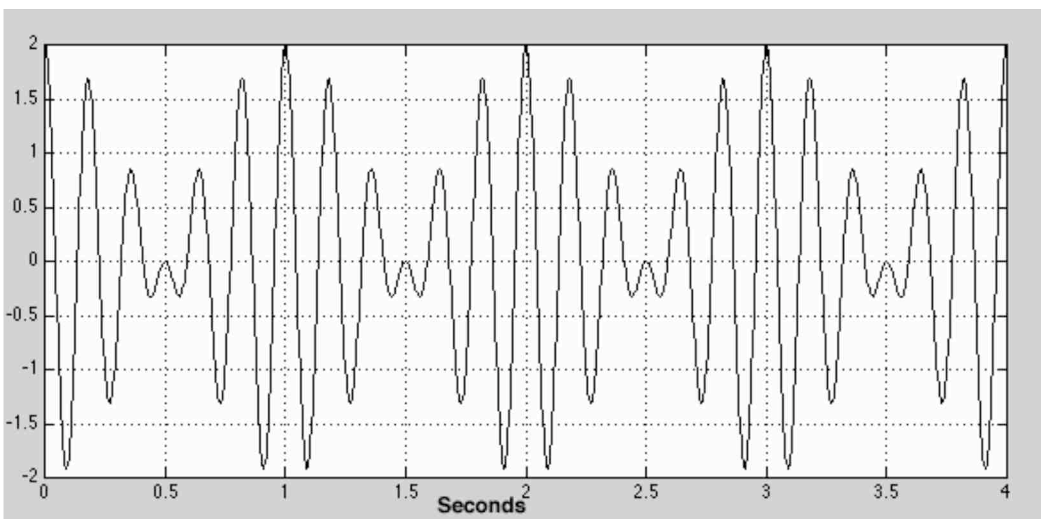
Now look at the red curve. In one second, it oscillates up and down 6 times. The frequency of the red wave is 6 Hz.

Suppose you are shaken by both waves at the same time. At time zero, you are shaken in the upward direction by both the red and blue waves; their effects add, and you will move up by 1 + 1 = 2 centimeters. Look at what happens at 0.5 seconds. The red wave is pushing you up by 1 centimeter, and the blue wave is pushing you down by 1 centimeter, so the two effects cancel, and at that instant you will be at level ground.

Note that there are also times when both waves are pushing you down. There's no place when they are both exactly at their minima, but they come pretty close at about 0.1 seconds. At this time both red and blue waves are down near -1 cm, so the sum effect will be to lower the ground by a total of 2 centimeters.

Beats

If we add the red and the blue waves, point by point, we get the oscillation shown below:



The curve is taller because it ranges between 2 and -2. The shaking is not as regular, because of the alternating reinforcement and cancellation. Try counting cycles, and see what you get.

You probably got a frequency of 6 Hz (that's what I got). But some of the cycles are much bigger than others. Mathematically, we would not try to characterize this oscillation by a single frequency; it is a superposition (sum) of two frequencies.

If you felt this combination of waves under you, would say that the shaking was modulated, with the biggest shaking taking place every 1 second (at 0, 1, 2, 3, 4, ...). These are called the beats. The beat frequency is given by an elegant equation:

$$f\ (\text{beats}) = f_1 - f_2$$

where f_1 and f_2 are the two frequencies that make up the signal (i.e. they are the frequencies of the red and blue waves). If the number comes out negative, ignore the sign; that's because beats look the same if they are upside-down.

To demonstrate beats, you can listen to two tuning forks with slightly different frequencies. The demonstration that we use at Berkeley is described at: http://www.mip.berkeley.edu/physics/B+35+20.html

For a very nice computer demonstration of how water waves can interfere, look at the UCLA site:
http://ephysics.physics.ucla.edu/physlets/einterference.htm
This site needs a fairly up-to-date browser with Java installed. You may already have that without knowing it, so it is worth trying. Move the red dots around, and then click on "calculate." Waves will come out of the two spots. These waves will add ("reinforce") at some locations, and cancel at others.

Musical notes

A musical note usually consists of a sound waves that has one dominant frequency. The middle white key on a piano, known as middle C, has a frequency of 256 Hertz (at least when the piano is tuned to the "Just scale"). The white keys are designated A, B, C, D, E, F, G, A, B, ... with the eight different letters which repeat in cycles. They repeat because, to most people, two consecutive Cs sound similar. They are said to be one "octave" apart. In fact, when you go one octave (eight notes), the frequency is exactly doubled. So the C above middle C has a frequency of 512 Hz. The next C has a frequency of 1024 Hz. Normal human hearing is quite good up to 10,000 Hz, and some people can hear tones as high as 15 to 20,000 Hz.

If two notes are played at the same time, and their frequency differs by just a little bit, then you will hear beats. Suppose you have a tuning fork that you know has a frequency of 256 Hz. You play the C string on a guitar, and listen to it and the tuning fork together. If you hear one beat per second, then you know the guitar is mistuned by 1 Hz; it is either 255 Hz or 257 Hz. You adjust the tension on the string until the frequency of the beats gets lower and lower. When there no longer are beats, the string is "in tune."

The interval between the A note and the higher E note is called a "fifth" because there are five notes: A, B, C, D, E. Likewise, middle C and the higher G make a fifth: C, D, E, F, G.

A violin is tuned so that the fifth has two frequencies whose ratio is exactly 1.5. So, with the middle C tuned to 256, then the G above middle C has a frequency of 379 Hz. This combination is also considered particularly pleasant, so many chords (combinations of notes played simultaneously, or in rapid sequence) contain this interval, as well as octaves.

The next most pleasant interval is called the "third." C and E would make a third. The ratio of notes for a perfect third is 1.25 = 5/4. The pleasant reaction of the sound is believed to be related to the fact that these frequencies have ratios equal to those of small whole numbers.

vibrations and the sense of sound

The middle C on a piano vibrates 256 times per second. The C below that is 128 Hz. The next lower C is 64 Hz, and the one below that is 32 Hz. That's pretty slow. If you can find a piano, play that note. Try singing it. Can you sense that your vocal cords are only vibrating 32 times per second? You almost feel that you can count the vibrations ... but you perceive the tone as a tone, not as a collection of vibrations. If a light flickers at 32 times per second, you sense it as flickering, but your eye is more sensitive to the rapid changes than your ear. TV sets in Europe flicker at 50 Hz, and many people notice that. In the United States, TVs flicker at 60 Hz; most people do not perceive this! It is strange that the eye responds so differently to 50 Hz than to 60 Hz.)

Ordinary house electricity oscillates 60 times per second, from positive to negative, and back. Sometimes this causes a buzz in electronics, or in a faulty light bulb. The buzz is actually 120 times per second, since both the positive and the negative excursions of the current make sound. Do you remember hearing such a buzz? Can you hum the buzz, approximately? That is 120 Hz.

Noise-canceling earphones

Because sound is a wave, it can be cancelled, just like the shaking of an earthquake. So some smart people have made earphones that have a built-in microphone on the outside. This microphone picks up noise, reverses it, and then puts it into the earphone speakers. If done correctly, the reversed sound exactly cancels the noise, and the wearer hears “the sound of silence.” On top of this quiet, the electronics can put music into the earphones. Since the music does not reach the outside microphone, it is not cancelled.

I have a set of Bose noise-canceling earphones, and I use them (mostly) on airplane flights. The result is that I can listen to high quality classical music, or to a typical airplane movie, and hear it as clearly as I would in a movie theater.

There are even more expensive versions of noise-canceling earphones that are used by professional pilots and others who work in very noisy environments. It would be very nice to be able to cancel noise over a much larger region, e.g. in an entire room. However that is probably not possible, at least not from a single small speaker. The reason is that the wavelength of sound (see next section) is typically 1 meter. If the noise is not coming from the same location as the speaker, then although the sound could be cancelled in one location, it would probably be reinforced in a different location. That is not a problem for earphones, since the entire earphone is so small. Noise cancellation for an entire room might be possible if the walls of the room were made out of loudspeakers.

Wavelength of a wave

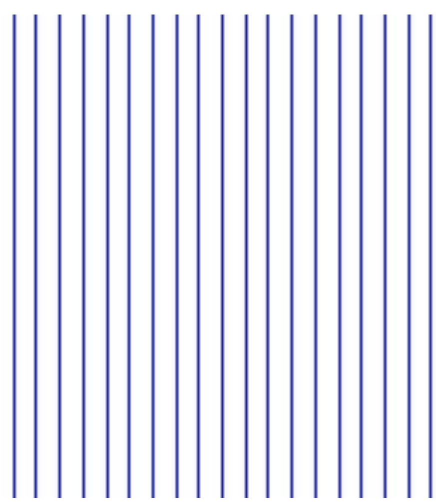
If a wave repeats itself in time, then the number of times it repeats every second is called the frequency. As the wave travels through space, it also repeats itself in shape, and the distance you have to go to go from one crest to another (or from one trough to another) is called the wavelength. There is a very simple relationship between the velocity of a wave v, its frequency f, and its wavelength L. That relationship is[10]:

$$v = f\,L$$

This equation is extremely useful, since you often know two of the three quantities, and need to figure out the third. For example, let's figure out the wavelength of sound for middle C on a piano. That has f = 256 cycles/sec. You learned in Chapter 1 that the velocity of sound is about 330 meters per second in air. So the wavelength is L = v/f = 330/256 = 1.3 meters.

Optional: why do waves bend towards the slow side?

Imagine you are in an airplane, and you are watching waves on the ocean. Draw lines on the crests of the waves, i.e. on the highest points. Suppose the waves are moving to the right. The image will look like this:

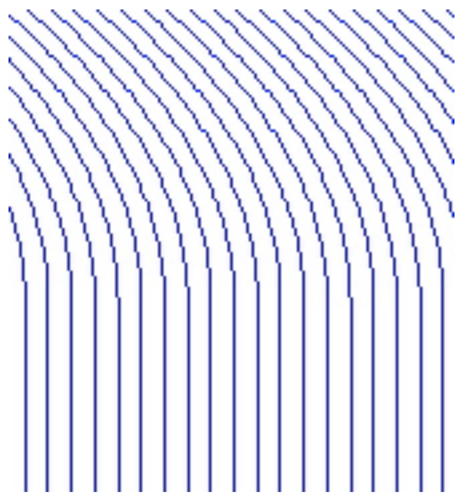


[10] Can you see why this equation is true? Try drawing a picture. Suppose you have a wave that has many crests. The number of crests that passes by any one point every second is f, the frequency. So what length of the wave must pass by that point? With f cycles, each one being a distance L long, the length of wave that passes by each second must be f times L. That's the equation.

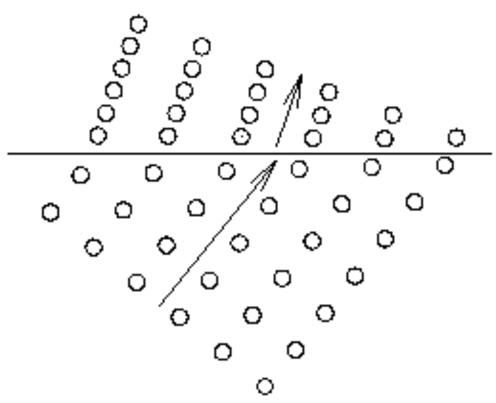
Look carefully at this image. The lines are the crests, i.e. they are the high points of the waves. The waves are all moving towards the right. That means that if we had a movie, each crest (i.e. each line) would move towards the right. In between the lines are the low points of the water waves, called the "troughs." They move too.

Recall that the distance between the crests is called the wavelength. In the figure, the wavelength is the separation of the lines.

Now imagine the waves moving to the right, but the ones near the top of the picture moving slower than the ones at the bottom. The lines would have to distort for this to be true. This is what it would look like:



The waves near the top are moving to the right, but slower than the ones near the bottom. They will arrive at the right edge later. Notice how the slowing tends to bend their direction. The same thing would happen with a marching band (assuming that adjacent band members held hands), seen from above, if the field near the top was muddy and the members marched slower than the ones near the bottom. This is illustrated in the figure below.



borrowed from http://www.lhup.edu/~dsimanek/scenario/analogy.htm

But also notice that the waves near the top are becoming diagonal. The crests are no longer straight up and down. The direction of the wave is perpendicular to the crest. So the wave is no longer moving from left to right, but is also moving slightly upward. The direction has changed towards the side that has slower velocity.

This method of explaining wave direction change is called "Huygens Principle."

end of chapter

Quick review

Waves travel in many materials, such as water, in air, in rock, in steel. Even though the material only shakes, the wave moves long distances. Waves are longitudinal when the direction of vibration is along the direction of the wave. Longitudinal waves include sound waves and the P earthquake wave. Waves can also be transverse. This means that the shaking is perpendicular to the direction of motion. An example is a wave on a rope. Water waves are both transverse and longitudinal. Light waves travel in a vacuum or in a material such as glass. They consist of a shaking electric and magnetic field. Light waves are transverse. Electrons and other particles are actually waves too, but they are so short ("wave packets") that this was not discovered until the 20^{th} century. The fact that particles are waves is called the theory of Quantum Mechanics.

If a wave repeats, then the number of repeats per second is called the frequency. For sound, frequency is the tone, i.e. high pitch or low pitch means high frequency or low frequency. For light, frequency is color. Blue is high frequency and red is low frequency. The wavelength is the distance between crests of the wave.

The velocity of the wave depends on the material it is passing through. Sound travels about one mile every 5 seconds through air, but one mile per second in water, and even faster in rock and steel. Light travels at one foot per billionth of a second, i.e. one foot per typical computer cycle. That is 186,000 miles per second.

The speed of sound depends on the temperature of the air. In hot air, sound travels faster. If sound is traveling horizontally, but the air above or below has a different temperature, then the direction of the sound will bend towards the side that is slower. This phenomena causes sound to get trapped beneath the ocean, and is exploited by whales to send sounds thousands of miles. It also was used by the military for sofar (locating downed pilots) and for SOSUS (to locate submarines). If four different microphones can pick up the same sound, then the source of the sound can be located. The same principle is used using radio waves for the GPS system.

A sound channel in the atmosphere is created because of the high altitude heating caused by the ozone layer. Project Mogul took advantage of the sound channel in the atmosphere. It was designed to detect Soviet nuclear tests. When the flying microphone disks crashed near Rosswell New Mexico in 1947, stories began to spread about flying saucers.

When the ground is cool, sound bends downward, and that lets us hear distant sounds. When the ground is warm, sound bends upward, and we do not hear distant sounds.

The velocity of sound waves does not depend on their frequency or wavelength. If it did, it would be hard to understand speech from someone standing far away. But the velocity of water waves does depend on the frequency and wavelength. Long wavelength water waves travel faster than short wavelength ones. Very long wavelength water waves, usually triggered by earthquakes, are called tsunamis or tidal waves.

Earthquakes begin when a fault ruptures at the epicenter, but they then travel as waves to distant places. The Richter scale gives a rough idea of the energy released. One point in the Richter scale is about a factor of 10 to 30 in energy released. The P wave is a compressional wave that travels fastest. Next comes the S wave (transverse) and finally the L wave. The time between the P and the S wave can be used to tell the distance to the epicenter. The fact that S waves do not travel through the center of the Earth enables us to deduce that there is liquid there, probably (from the velocity we measure) liquid iron.

Waves can cancel, and that gives rise to beats (in music) and to strange effects, such as buildings that feel no shaking because of the fact that two canceling earthquake waves approached the building from different directions.

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essay questions

Discuss the noticeable and/or important effects that arise from:

(1) the cancellation and reinforcing of waves

or

(2) the different velocities of waves as they travel though different parts of the same material

Water waves and sound waves are both waves, despite the fact that they appear to be dissimilar to most people. Describe the way that they are both waves, properties they both share. What properties of sound make it clear that sound is really a wave?

Everyone knows that an earthquake is the shaking of the ground. Describe the ways in which it acts like a wave. How can the S and P waves be used to determine the location of the epicenter, and the nature of the interior of the Earth?

Describe the properties of sound underneath the ocean surface. Describe how it moves, and the implications of this for life (wild and human) under the water.

Describe how sound travels in air near the surface of the Earth. How does it depend on time of day, and weather conditions? What interesting phenomena can an observant person notice?

According to the text, what were the “flying disks” that crashed near Roswell New Mexico? Describe the formerly classified program that they were to be used for. Make sure to include all the relevant physics.

The sofar disks used by the Navy had remarkable properties. Describe how they work, and how they were intended to be used. Make sure to include all the relevant physics.

short questions

What is a wavelength?
- ( ) the length of the crest of a wave
- ( ) the distance between crests
- ( ) the depth that a wave has zero motion
- ( ) the distance between crest and trough

Water waves tend to move:
- ( ) slower in shallow water
- ( ) faster in shallow water as they break
- ( ) slower in deep water
- ( ) The same speed in shallow water as in deep water

Which travels fastest?
- ( ) L wave
- ( ) S wave
- ( ) P wave
- ( ) they all travel at the same speed

An earthquake waves does its worst damage when it reaches an area that
- ( ) slows it down
- ( ) increases its frequency
- ( ) decreases its frequency
- ( ) adds additional energy

Sofar took advantage of
- ( ) the sound channel in the ocean
- ( ) the sound channel in the atmosphere
- ( ) the magnetic field of the earth
- ( ) the uncertainty principle

As you move to a higher altitude, the temperature of the air
- ( ) first gets cooler, then warmer
- ( ) stays constant, then gets cooler
- ( ) first gets warmer, then cooler

In music, an "octave" refers to two frequencies that differ by a factor of
- ( ) eight
- ( ) four
- ( ) two
- ( ) one

If we double the frequency of sound, the wavelength is
- ( ) doubled

( ) halved
( ) unchanged
( ) quadrupled

Which of the following was true about project Mogul?
( ) It was concerned with the atmosphere
( ) It resulted in the first nuclear bomb
( ) It led to the discovery of nuclear fission
( ) It involved the invention of integrated circuits

According to this text, the “Flying Disks” of Roswell were:
( ) advanced space vehicles
( ) nuclear weapons
( ) microphones
( ) alien devices of undetermined purpose

Which of the following is NOT true?
( ) primary waves are longitudinal
( ) secondary waves are transverse
( ) surface waves do the most damage

You are most likely to be able to hear distant sounds in the evening because
( ) sound bends upwards, away from the ground
( ) sound is most likely to travel in a straight line at that time
( ) sound bends downwards towards the ground

GPS works by:
( ) sending signal to satellites that then radio back the location
( ) receiving signals and calculating the position
( ) detecting the position of the sound channel in the atmosphere

If the distance between P and S waves is 10 seconds, how far from the epicenter are you?
( ) 8.4 km
( ) 20 km
( )84 km
( )840 km

Sound moves slower near the troposphere. This occurs because this region of the atmosphere
( ) contains ozone, and sound is slow in ozone
( ) is colder
( ) is less dense
( ) is above the clouds

The flying disks of project Mogul took advantage of

( ) the oceanic sound channel
( ) the sofar signally system
( ) the oceanic sound channel
( ) the low sound velocity at the tropopause

We know that the inner part of the Earth is liquid because:
( ) No S waves move across it
( ) We can detect the flow of material from the emitted sound
( ) At such great pressures, everything becomes liquid
( ) neutrinos pass through it and show the pattern

The same note is heard on two pianos. Beats are heard once per second. From this we deduce:
( ) at least one of the pianos is out of tune (the notes are at the wrong frequency)
( ) both pianos are out of tune
( ) the pianos have been accurately tuned
( ) the pianos will sound especially pleasant if played together

The crack of a bullwhip occurs when
( ) the end moves faster than the speed of sound
( ) the end triggers an electron avalanche and makes a spark
( ) the end smacks against the air, briefly creating ions
( ) the end causes a phase change in the vacuum

A pianist plays two keys: middle C, and the C above middle C (i.e. an octave higher). The speed of sound for the higher frequency, compared to that for the lower frequency, is (careful: possibly a trick question):
( ) the same
( ) 2 x faster
( ) 2 x slower
( ) sqrt(2) faster

During a typical day, sound emitted near the ground tends to bend:
( ) upwards, towards the sky
( ) downward, towards the ground
( ) not at all; it goes straight

AC stands for
( ) Alternating Current
( ) Alternative Current
( ) Accelerated Current
( ) Awful Current

Very long wavelength water waves travel:
( ) at the same speed as short wavelength waves
( ) slower than short wavelength wave

( ) faster than short wavelength waves
( ) some faster, some slower, depending on frequency

The sound channel in the ocean carries sound a long distance because
( ) the ocean doesn't absorb sound at that level
( ) whales pick listen to the sound and sing it over, increasing its volume
( ) the pressure of the ocean at that depth makes sound louder
( ) the sound doesn't spread out in the up or down directions

When there is an inversion
( ) sound tends to bend upward
( ) sound tends to bend downward
( ) sound is strongly absorbed
( ) sound is amplified